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SOIL EROSION BY SURFACE WATER FLOW ON A STONY, SEMIARID HILLSLOPE

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ABSTRACT

Soil erosion on hillslopes occurs by processes of soil splash from raindrop impacts and sediment entrainment by surface water flows. This study investigates the process of soil erosion by surface water flow on a stony soil in a semiarid environment. A field experimental method was developed whereby erosion by concentrated flow could be measured in predefined flow areas without disturbing the soil surface. The method allowed for measurements in this study of flow erosion at a much wider range of slopes (2·6 to 30·1 per cent) and unit discharge rates (0·0007 to 0·007 $m^2\ s^{-1}$) than have been previously feasible. Flow velocities were correlated to discharge and hydraulic radius, but not to slope. The lack of correlation between velocity and slope might have been due to the greater rock cover on the steeper slopes which caused the surface to be hydraulically rougher and thus counteract the expected effect of slope on flow velocity. The detachment data illustrated limitations in applying a linear hydraulic shear stress model over the entire range of the data collected. Flow detachment rates were better correlated to a power function of either shear stress ($r^2 = 0{\cdot}51$) or stream power ($r^2 = 0{\cdot}59$). Published in 1999 by John Wiley & Sons, Ltd.

KEY WORDS: soil erosion; rocks; hydraulics; hydraulic roughness; rill erosion

INTRODUCTION

Generally where water erosion rates on upland areas are greatest, soil detachment by surface water flow is active. Flow depths in small concentrated flow areas on hillslopes, often termed rills, are typically on the order of a centimetre or less and slopes may be quite steep. In general, rill erodibility (as defined in the Water Erosion Prediction Project Model) on relatively undisturbed rangelands is an order of magnitude or more less than for disturbed cropland soils (Laflen *et al.*, 1991). For the Woodward soil reported in that study, for example, cropland rill erodibility was reported as 0·025 s m^{-1}, while rangeland rill erodibility was reported as 0·0001 s m^{-1}. The small difference in the soil texture between the rangeland and cropland Woodward soils was not sufficient to explain this 250-fold difference in susceptibility to rilling. Yet rangelands erode. The Stronghold soil located at the Lucky Hills site at Walnut Gulch in southeastern Arizona has apparently experienced a great deal of erosion in the past 30 years, if the evidence of up to 25 cm of exposed roots on the vegetation at particular locations there is reliable (Nearing, pers. obs.). Sediment records from Walnut Gulch, AZ, for the LH5 watershed, which is located adjacent to the current study area, have averaged approximately 0·5 t ha^{-1} yr^{-1} over the past 10 years (J.R. Simanton, pers. comm.).

Recent studies of rills in cropland soils have challenged previously held beliefs regarding the hydraulics and erosion of surface water flows. An analysis of a compilation of data from six experiments showed that the use of the traditional velocity and roughness relationships such as the Chezy and Manning equations have limited value in eroding rills because of the insensitivity of velocity to slope (Nearing *et al.*, 1997). This result is apparently related to the fact that rill roughness tends to be greater at steeper slopes because of the greater

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erosion-induced roughness for the steeper conditions. Recent studies in cropland soils have also shown that stream power, ω, is a better hydraulic predictor variable than several other proposed variables, including unit stream power, shear stress, effective stream power, and shear stress partitioned by the Darcy–Weisbach hydraulic roughness coefficient (Nearing *et al.*, 1997; Elliot and Laflen, 1993).

Previous investigations of erosion on rangeland soils have used primarily larger (3 m by 10 m) plots under rainfall simulators, wherein processes of splash and flow erosion are both active (Simanton *et al.*, 1987; Laflen *et al.*, 1991). In this case, because of the complexity of interactions of erosion processes, the analysis for soil erodibility parameters is not trivial and must be done by optimizing the parameter values by minimizing differences between model predictions and measured soil losses (Nearing *et al.*, 1989a). The optimization process is complicated, but the resulting parameters tend to be reliable for use with the particular model of interest as long as the model is used within the range of conditions represented by the rainfall simulator tests.

Govers (1992) developed a relationship for mean flow velocity and total discharge in eroding rills on loamy soil using data from four studies. The relationship took the form:

$$V = 3 \cdot 52Q^{0{\cdot}294} \tag{1}$$

where V (m s^{-1}) was mean flow velocity and Q (m^3 s^{-1}) was total rill discharge. One implication of Equation 1, as noted by Govers (1992), is the absence of a clear slope effect on velocity, which makes the use of roughness relationships such as the Darcy–Weisbach, Chezy or Manning equations of somewhat limited usefulness for eroding rills on hillslopes. Abrahams *et al.* (1996) tested Equation 1 on seven rills at Walnut Gulch, AZ, on a semiarid, stony hillslope which they stabilized with a glue mixture prior to testing. The experimental method involved the measurement of inflow rate and cross-sectional area of the flow, from which flow velocity was computed. Slopes ranged from 1·3 to 5·6 per cent. Abrahams *et al.* (1996) found velocity to be correlated to (in order of significance) total discharge, percentage gravel, and slope. Their velocities fell well below the line predicted by Govers (Equation 1).

The objectives of this study were to evaluate the hydraulics and erosion by surface water flow of stony soil in a semiarid, rangeland environment. Methods for directly measuring rill erosion rates on undisturbed soil surfaces allowed measurements over a wide range of slopes and discharge rates. The measurements were used to evaluate flow velocity as a function of slope, discharge and rock cover, and to evaluate soil detachment rates as a function of hydraulic shear stress, stream power and hydraulic friction.

METHODS

Experiments were conducted at the Lucky Hills site of the Walnut Gulch watershed near Tombstone, AZ. The soil was a Stronghold coarse-loamy, mixed, thermic ustochreptic calciorthid. The surface material (0–9 cm depth) was a gravelly sandy loam with an average of 10 per cent clay, 8 per cent silt, 39 per cent sand and 43 per cent rock fragments along the mid-slope sections. The site is located in the Chihuahuan desert and the vegetation is characterized as shrub.

Throughout this paper we refer to the soil testing areas as 'flow areas' or 'rills' interchangeably. In essence we attempted to mimic the process of sediment removal from shallow flow areas which act in a similar way to small channels or 'rills' found on hillslopes. These artificial rills in contrast to natural rills, however, were straight and of constant flow width.

The flow areas were formed with minimal disturbance of the test surface by placing a wooden plank 3·05 m long and 0·14 m wide along the hillslope at the desired location (Figure 1). This was the surface area also used for calculations of soil detachment rates. A testing surface was selected only if it was clear from large debris and plants, and if it appeared to be an area which was exposed to surface water runoff. Sampling areas were selected to obtain a range of slope gradients along a specific hillslope, but within a single soil type area. Tested slopes ranged from 2·6 to 30·1 per cent. Slope was measured with a digital protractor placed along the plank at several points. A hole was dug in the ground at the lower end of the plank for the purpose of collecting the runoff and sediment samples. Soil material from the hole was then placed along the edge of the

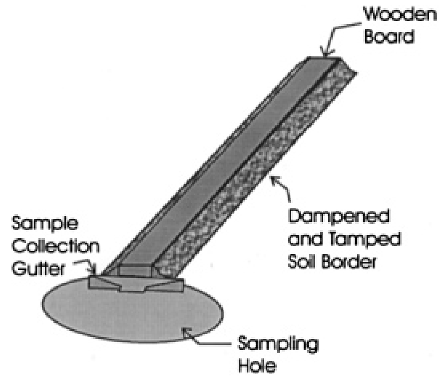

Figure 1. Schematic diagram of experimental set-up

plank along its entire length, wetted slightly, and then tamped into place by foot. The board was then removed, exposing the soil surface testing section. Experience showed that when the soil borders were prepared at the right water content and tamping they were stable during the experiment in the sense that the flow was confined and the sides did not erode.

Clear water was gravity fed through a hose from a water tank to the tops of the rills at increasing rates of approximately 9·6, 19·2, 28·8 and 57·6 l min^{-1}. Approximately one minute was allowed to pass after the first water reached the sample collection gutter at the bottom of each rill before samples were taken, in order to flush out any sediment that might have inadvertently fallen on the rill during the preparation process. Three sediment, runoff rate, and velocity measurements were taken at one minute intervals at each flow rate. Velocity was measured using the leading edge fluorescent dye technique with a correction factor of 0·8 for mean velocities (King and Norton, 1992).

Measurement of rock cover in the rill was made between each inflow rate on each plot. This was done using a tape and pin technique. A measuring tape was laid out along the rill length and a pin was lowered at even spacing along the rill in 20 places. Rock or soil was recorded for each point.

Detachment rate, D_r (kg s^{-1} m^{-2}), was calculated simply as the mass of sediment leaving the flow area per unit time per unit surface area (0·427 m^2) of the flow area. The flow rates were great enough, and development of scour channels in the bed was low enough, such that the entire bed area with width of 0·14 m was covered by the flow of water. In other words, the flow was confined by the soil borders and the flow width was considered to be 0·14 m. Hydraulic radius, R (m), was calculated based on the measurements of flow velocity and discharge, assuming a rectangular, constant-width flow stream.

RESULTS AND DISCUSSION

Hydraulics

Flow Reynold's numbers ($Nr = RV/\nu$) ranged from approximately 600 to 6000, and the Froude number ($Fr = V/(Rg)^{1/2}$) ranged from approximately 0·4 to 1·4, where R (m) is hydraulic radius of flow, V (m s^{-1}) is average flow velocity, ν (m^2 s^{-1}) is the kinematic viscosity of water, and g (m s^{-2}) is the constant acceleration of gravity. Thus the flows fell in transitional to turbulent flow regimes, and included both subcritical and supercritical flows.

Velocity, V (m s^{-1}), was highly correlated ($\alpha = 0{\cdot}01$) with both hydraulic radius, R (m) and total discharge, Q (m^3 s^{-1}). The correlations between V and slope, S, and between V and rock cover, Rx, however, were not significant. The best predictor for V from this data set was total discharge, Q. The linear regression between V and Q yielded a coefficient of determination of 0·90. We chose, however, to plot V as a power function of Q

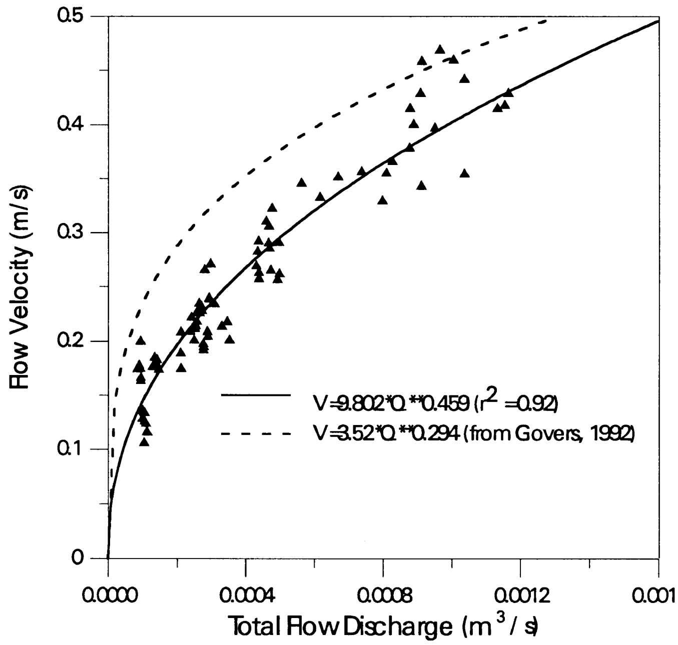

Figure 2. Relationship for average flow velocity as a function of total flow discharge

(Figure 2) since that relationship makes more physical sense at very low discharge rates. Thus we derived the equation:

$$V = 9 \cdot 802\, Q^{0 \cdot 459} \quad (r^2 = 0 \cdot 92) \tag{2}$$

While the equation is somewhat different (velocities were lesser) from that reported by Govers (1992) (Equation 1), the data from this experiment did fall within the envelope of data reported by Govers. Non-linear regression between V and power functions of S and R, as are used in the Chezy and Manning equations, produced a poorer fit ($r^2 = 0 \cdot 77$) than that given by Equation 2 and the addition of rock cover percentage did not increase the statistical fit for V.

These results corroborate those reported by Govers (1992) and Nearing *et al.* (1997) for other soils which suggests that flow velocity is well characterized by flow discharge rates, and is basically independent of slope. In the case of the study of Nearing *et al.* (1997) the independence of flow velocity from slope was attributed to differences in the physical roughness of the rill. The steeper rills in the silty soil used in that study tended to have more headcuts, which formed at various places along the rill length and moved generally upslope with time. These headcuts probably significantly increased the hydraulic roughness of the surface. Roughness differences may also be a factor in this experiment. The measurements of rock cover measured in this study show a dependence between rock cover fraction and slope gradient (Figure 3). This result is consistent in form to relationships from previous studies on rock cover (Poesen *et al.*, 1998; Simanton *et al.*, 1994; Simanton and Tory, 1994; Yair and Kline, 1973) The Darcy–Weisbach coefficient was computed for these data, and is plotted in Figure 4 as a function of rock cover.

There are two possible explanations for the relationship illustrated in Figure 4. One explanation is that the rock cover indeed does induce a hydraulically rougher surface which tends to decrease the flow velocity in a relative sense. If this is true, then it can explain why there was no observed dependence between flow velocity and slope in these data. The tendency for velocity to increase as a function of slope would be offset by the fact that the steeper slopes have a greater rock cover, and hence hydraulic roughness, which tends to decrease the

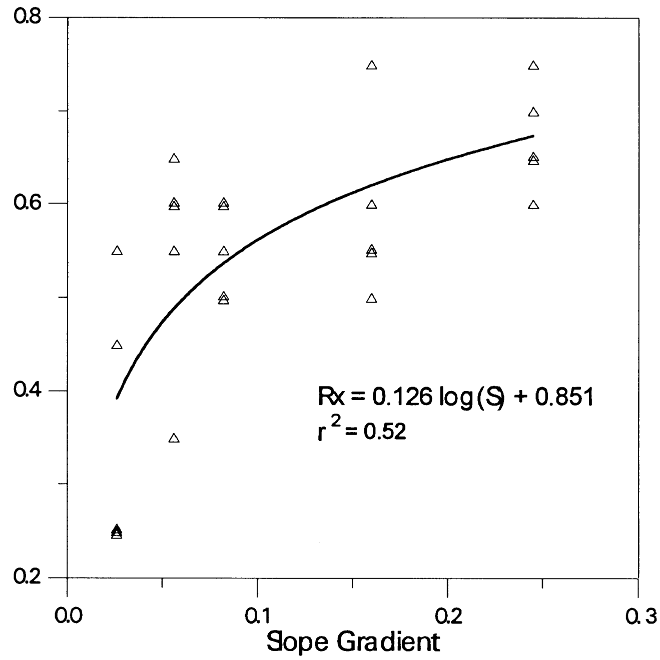

Figure 3. Relationship for rock cover fraction as a function of slope

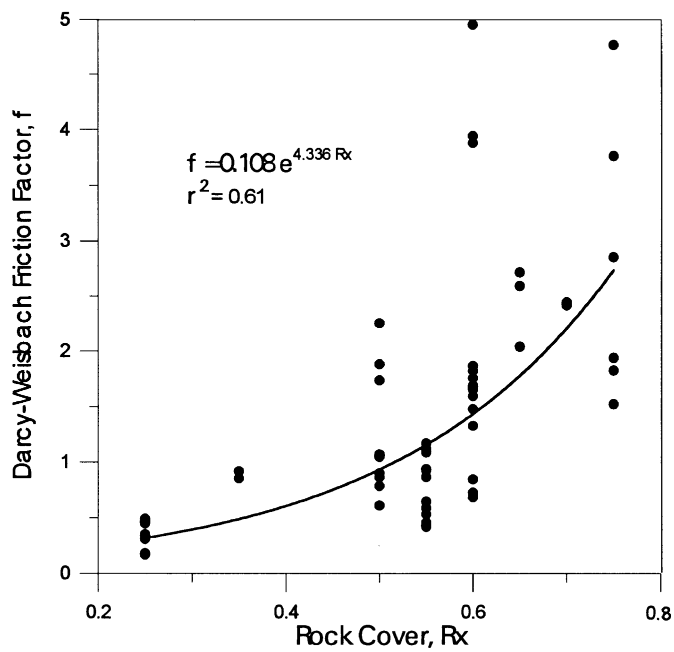

Figure 4. Relationship for the calculated Darcy–Weisbach friction factor as a function of rock cover fraction

velocities. However, since the Darcy–Weisbach equation from which the parameter f is calculated assumes a relationship between velocity and slope, the correlation between the calculated Darcy–Weisbach roughness parameter, f, and rock cover might be essentially spurious. Since we have no data at this time for the same rock cover on different slopes, or for different rock covers on the same slope, we cannot conclude which line

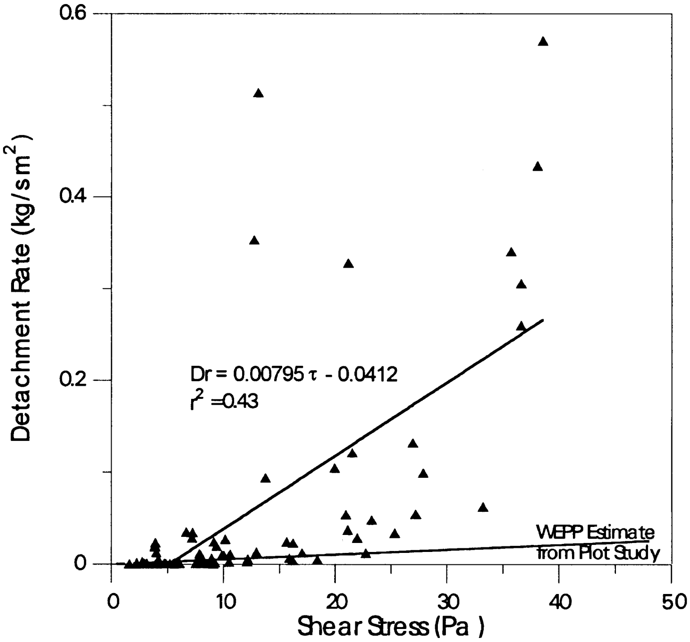

Figure 5. Relationship for average soil detachment rate as a linear function of hydraulic shear stress

of reasoning better explains the results from this experiment. On the other hand, since in nature rock cover in the semiarid environments tends to increase with increasing slope (Poesen *et al.*, 1998; Simanton *et al.*, 1994; Simanton and Tory, 1994), the V vs. Q relationship should be useful for field application in either case.

Erosion

Detachment rate in the rills was computed as the sediment yield divided by the flow area. Most erosion models assume linear relationships for soil detachment in rills as a function of some hydraulic variable, often either shear stress (Nearing *et al.*, 1989a), unit stream power (Morgan *et al.*, 1992; Morgan, 1995) or stream power (Rose *et al.*, 1983a, b; Hairsine and Rose, 1992a, b). A rainfall simulator experiment (Simanton *et al.*, 1987) was conducted at the Lucky Hills site for determination of erodibility parameters for the Water Erosion Prediction Project (WEPP) (Nearing *et al.*, 1989b) model in 1988. Results of the experiment were analysed using optimization techniques as outlined by Nearing *et al.* (1989a), and a summary of the results was presented by Laflen *et al.* (1991) for the shear stress model. Hydraulic shear stress is computed as:

$$\tau = \rho_w g R S \tag{3}$$

where ρ_w (kg m^{-3}) is the density of water, S (m m^{-1}) is slope gradient, and R (m) is the hydraulic radius. According to the terminology used for the WEPP model, if one were to plot the detachment rate in the rill as a function of hydraulic shear stress, the slope of the regression line is the rill erodibility parameter, K_r, and the intercept on the x-axis (shear stress axis) is the critical shear stress, τ_c. The erodibility values reported for the Lucky Hills site, on the same general location and soil used in the current study, were 0·00053 s m^{-1} and 0·5 Pa for K_r and τ_c, respectively (Laflen *et al.*, 1991).

Detachment rate was not particularly well predicted by a linear function of shear stress for the current data set (Figure 5). Using simple linear regression between detachment rate and shear stress gave values of 0·00795 s m^{-1} and 5 Pa for K_r and τ_c, respectively. These values are an order of magnitude different from those found in the WEPP plot study. This is a large difference, but perhaps not as great as it appears at first

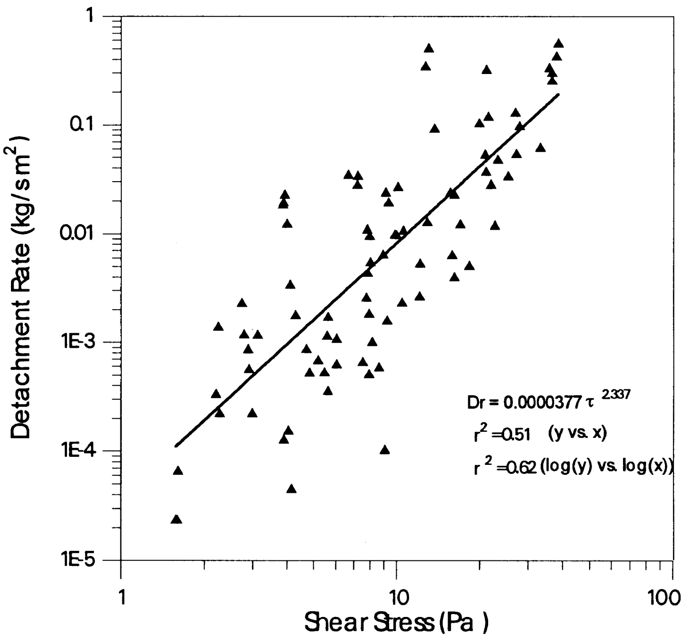

Figure 6. Relationship for average soil detachment rate as a power function of hydraulic shear stress. The first coefficient of correlation is for the linear relationship between the response variable and the predictor function; the second is for the log-transformed fit, which was the method used to develop the best-fit function

glance when one realizes that K_r and τ_c have inverse effects on predicted sediment yield in WEPP. A larger K_r value will offset a larger τ_c value in terms of overall prediction of sediment yield. One reason for the difference between the results of the studies may the range of shear stresses and slopes studied. While the rainfall simulator plots were confined to slopes of approximately 10 per cent, slopes in the current study ranged up to 31 per cent. Also, the flow rates in the concentrated flow channels on the rainfall simulator plots were undoubtedly much lower. Typically the values of shear stress in those types of studies do not exceed 10 Pa. At values of under 10 Pa for the data in this study, the computed erodibility values would be closer to the values from the WEPP simulator plots.

Another reason for the discrepancy in computed erodibility values may simply be the differences in experimental methods between this study and that of Laflen *et al.* (1991). The field studies reported by Laflen *et al.* (1991) were conducted using rainfall simulators on plots 3 m wide by 11 m long, along with added inflow of water to simulate longer slope lengths. The calculations of rill erodibility and soil critical shear stress from those plot data (Nearing *et al.*, 1989a) were made by optimization of the WEPP model and the sediment yield from the larger plots. The difference between the two erodibility estimates of this study and that of Laflen *et al.* (1991) probably points to limitations of WEPP to account for all of the erosion processes and their interactions. The important point here is that determination of model parameters must be appropriate to the scale of use. The study of Laflen *et al.* (1991) addresses the scale of hillslopes, and the erodibility parameters of Laflen *et al.* are more appropriate to use with WEPP, which is a hillslope scale erosion model.

Detachment rate was better fitted to shear stress with a power function (Figure 6). In this case the coefficient of determination between measured and predicted values was 0·51, as compared to 0·43 for the linear shear stress model. A better predictor of detachment was stream power, ω (kg s^{-3}), which is given by the function:

$$\omega = \rho_w g q S \tag{4a}$$

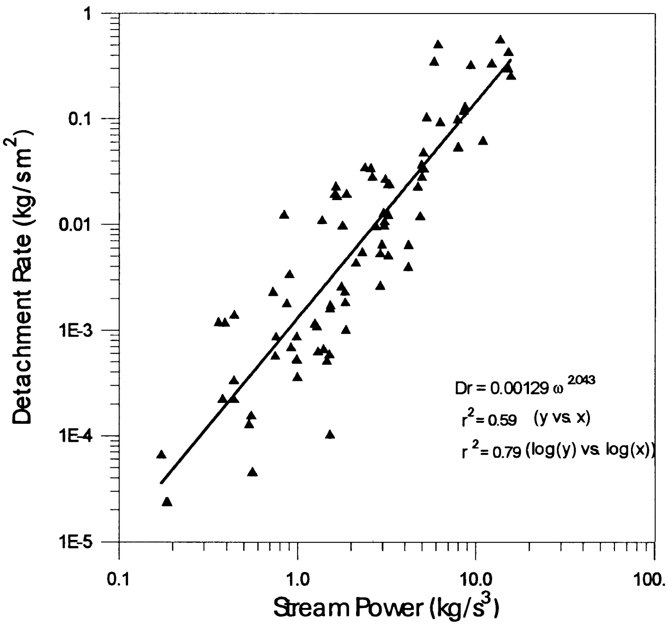

Figure 7. Relationship for average soil detachment rate as a power function of hydraulic stream power. The first coefficient of correlation is for the linear relationship between the response variable and the predictor function; the second is for the log-transformed fit, which was the method used to develop the best-fit function

or alternatively as:

$$\omega = \tau V \tag{4b}$$

where q (m^2 s^{-1}) is unit discharge of water (Figure 7). In this case the coefficient of determination between measured and predicted values was 0·59 for the function:

$$D_r = 0 \cdot 00129\,\omega^{2\cdot 043} \tag{5}$$

Other measured factors from the experiment were not significantly related to flow detachment, including rock cover percentage, velocity or hydraulic friction factors. This is significant in terms of our current use of erosion models. The WEPP model, for example, partitions flow shear stress according to hydraulic roughness in order to account for flow energy losses on residue roughness in croplands. While the partitioning might work well in the case of residue in cropland conditions, the theory of shear partitioning is apparently not universal, as it does not apply to these data.

CONCLUSIONS

This study corroborates several other recent laboratory and field studies on various soil types which show a lack of dependence between rill flow velocity and slope gradient (Govers, 1992; Nearing *et al.*, 1997; Takken *et al.*, 1998). This result is important, because in practice hydrologic and erosion modellers and model users use a type of runoff equation which assumes a dependence of flow velocity on slope. Often, too, experimentalists design experiments with the assumption of such a dependence, often without taking the data requisite to testing the assumption. The hydraulic roughness equations, such as the Chezy and Manning equations, are often parameterized, but rarely questioned. Yet these equations are of limited value for application to hillslope runoff in rills. If one must assume or estimate a change in roughness factors as a

function of slope such that the calculated velocities are slope independent, then the use of a function for velocity which is slope dependent is redundant. An alternative approach for modelling runoff velocity is the use of power function of discharge as suggested here and by Govers (1992). Additional research is needed in determining how rill hydraulics functions within the system of surface runoff routing on hillslopes.

One would expect from basic physical considerations that velocity should be a function of slope. The driving force for water flowing downhill is the component of the gravity force vector in the downslope direction, which is proportional to the sine of the slope angle. On stable surfaces, in fact, such a dependence does occur (Foster *et al.*, 1984; Abrahams *et al.*, 1996). On eroding surfaces, though, the situation is different because the erosion at different slopes affects different surface morphologies. In the case of rills on erodible, disturbed, cropland soils, the steeper rills tend to form headcuts and other erosion-induced roughness morphologies which create rougher surfaces and tend to counteract the slope gradient effect of velocity (Nearing *et al.*, 1997; Govers, 1992). For the case of consolidated soils containing rocks, as in this study, a possible explanation may be that erosion processes, and in particular armouring, cause the rock concentrations to be greater at the steeper slopes, which then act as hydraulic roughness elements which counteract the slope effect on velocity as slope increases. Certainly visual comparison between the morphologies on the two types of surfaces supports the idea that in both cases the steeper slopes are rougher, with erosional features being present on the more erodible surface and more distinct on the steeper slopes, and with rocks present on the less erodible semiarid surface and in greater quantity on the steeper slopes.

This study also corroborates recent experiments on cropland soil which indicate that stream power is a better hydraulic predictor variable for detachment and sediment yield than is shear stress (Nearing *et al.*, 1997; Elliot and Laflen, 1993). While this may not be of major concern for using the shear concept for models and design considerations when the conditions of application are with the same level of shear as in the experiments to assess soil parameters, the application could be much in error for the extreme erosion event.

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